Micromagnetic study of recording on ion-irradiated granular-patterned media

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Abstract

Micromagnetic simulations are used to study magnetic recording processes of ion-irradiated bit-patterned media. The media is composed of several hundred grains. It is assumed that the ion irradiation affects the magnetic anisotropy but keeps the magnetization unchanged. The recording simulations were performed using a fully integrated micromagnetic simulation package. The background region that is regarded to be irradiated triggers the magnetic switching of the bits. Thus some degree of intergrain exchange between bits and background is needed to reduce the write field. However, the intergrain exchange leads to spin waves. It is found that the spin waves may cause adjacent tracks erasure.

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1. Introduction

With increasing area density of magnetic recording, patterned media has been thought of one of the candidates for high-density recording media over 1 Tb/in\(^2\) [1]. Patterned media has a potential in noise reduction and may extend the superparamagnetic limit to higher densities [2–5]. However, patterned media has drawbacks as well. The main problem of patterned media is the complicated fabrication procedures including ion milling and the deposition of background non-magnetic material including e-beam writing. A possible fabrication process bases on focused ion beam (FIB) irradiation [6–10]. The ions irradiated onto the magnetic material may affect the composition and crystal structure of the material, which results in a change of the saturation magnetization and the magnetic anisotropy. Thus, ion irradiation enables to adjust the magnetic properties of the materials by varying the irradiating ion, controlling the dose and changing the irradiation time [10–12]. Therefore, both an increase as well as a decrease of the magnetization can be realized [9,10]. Magnetic force microscopy (MFM) [9,13], transmission electron microscopy (TEM) [14] and superconducting quantum interference devices (SQUID) [15] have been used to measure the magnetic properties. Although these techniques provide important insight they also have limitations such as interactions between the MFM tip and the specimen, they only provide information of the static state and the restrictions of the specimen shape and type.

Micromagnetics is an ideal tool for the simulation of complex nanoparticles and granular microstructures like patterned media. In order to study the write process of the individual bits for patterned media a finite element micromagnetic model has been used. It includes all interactions between the write head, the magnetic medium and soft under layer. The numerical model based on the Landau–Lifshitz–Gilbert equation fully takes into account the long range stray field coupling and exchange coupling between grains of the recording media.

In this paper, micromagnetic simulations are presented of ion-irradiated-patterned media. We have investigated
how exchange coupling between the soft region (irradiated region) and the hard region (not irradiated region) might influence the recording process on bit patterned media.

2. Micromagnetic simulation

We start from a granular media with perpendicular anisotropy. The recording media material is assumed to be Co_{46}Pt_{54}, which has high perpendicular anisotropy and well-decoupled grains [19]. The finite element media model is composed of 420 grains with an average diameter of 7 nm and a height of 15 nm. In experiment, the irradiation area can be selected by stencil masks or e-beam lithography [6,7]. We use the same assumption—the bits are protected from the irradiation by removable shadowing materials. Albrecht et al. [22] has studied the magnetic recording behavior of the patterned stripes prepared by ion irradiation experimentally. In the simulations, it is assumed that ion irradiation affects only the uniaxial anisotropy. The hard magnetic properties (\( K_U = 10^6 \text{J/m}^3 \)) are assigned to the grains within a recording bit whereas zero magnetocrystalline anisotropy is assigned to the irradiated region. The bit size was 30 \( \times \) 30 nm\(^2 \) that corresponds to 180 Gb/in\(^2 \). The material parameters for the recording media are as following: The saturation polarization \( J_{s\text{(bit)}} = J_{s\text{(irradiated)}} = 0.8 \text{T} \) and the exchange stiffness \( A_{\text{exch}} = 10 \text{pJ/m} \). In order to account for a possible change of the intergrain exchange, the intergrain exchange stiffness \( A_{\text{int}} \) is varied from 0.07 to 1.13 pJ/m of \( A_{\text{exch}} \) and \( \delta = 0.02 \). The bits are arranged 2 \( \times \) 2 with 60 nm pitch along the tracks and 45 nm spacing between tracks.

During the writing process, the write head moves across the multilayer structure composed of the recording media, spacer and the soft underlayer that returns the write field to the back yoke. The write field is generated by the current through the induction coil that surrounds the write head. We observed a maximum write field strength of 1 T. The time to establish the maximum head field after reversing the coil current is about 0.8 ns. The head velocity is 20 m/s. In patterned media, the recording bits are predefined, hence the synchronization of the field and bit position becomes important [16]. Considering the head field rise, the current was activated before getting 30 nm closer to the bit in our simulation [17,18].

The following material parameters are chosen for the head and the soft under layer. \( J_{s\text{(yoke)}} = 2 \text{T}, J_{s\text{(tip)}} = 2.4 \text{T}, J_{s\text{(SUL)}} = 2 \text{T}, \) and \( \delta = 0.1 \). The write head and the soft underlayer have a weak uniaxial anisotropy in the cross track direction, \( K_{U\text{(yoke)}} = 800 \text{A/m}, K_{U\text{(tip)}} = 800 \text{A/m} \) and \( K_{U\text{(SUL)}} = 800 \text{A/m} \). The easy axis of the media is along the perpendicular direction of the media surface. The easy axis of the soft underlayer is parallel to the surface. The Gilbert damping constant = 0.1 for the write head and soft underlayer. The distance between head to media and media to soft underlayer was 10 and 7 nm, respectively. The length of the trailing edge of the pole tip and the width of the pole tip is 75 and 115 nm, respectively (Fig. 1). Since the model consists of about 44,378 nodes, 101,477 elements and 81,197 surface elements for interaction calculation, the macro-spin assumption was used in order to save computational time. In the macro-spin assumption, the magnetization of each grain is assumed to be homogenous [21].

Fig. 1. (a) Finite element model of a perpendicular recording device for patterned media with a granular microstructure of the recording media. (b) Media model in detail. The gray scale shows the magnetization state of the media, the trapezoid and the arrow show the cross section of the write head and its moving direction, respectively. Four bits can be identified in the white and black regions.
3. Numerical results

The finite element method was used to simulate the magnetization processes of the patterned media composed of magnetically hard grains (bits) and soft grains (irradiated). The magnetization process was observed for 9 ns. After that time, the write head has passed two upper bits and has finally exited the media. The domain configuration of the media is observed during the write process. The head field changes its direction once during writing. When the field is applied, the soft magnetic region is reversed by the write field from the head. Then, the domain wall that is formed in the soft grains propagates into the hard phase. Fig. 2b shows the magnetization dynamics with $A_{\text{int}} = 0.37 \text{ pJ/m}$, which is 3.7% of the intergrain exchange. Therefore, in the case of weaker intergrain exchange coupling, a higher head field is required to write the bits. In the case of small intergrain exchange (Fig. 2a), we can see that bit writing fails. For larger exchange between the grains, the upper right bit can be reversed (Fig. 2b). This writing process is similar to that of exchange spring media [20]. The main difference between the exchange spring media and ion-irradiated-patterned media is the relative position of the hard magnet and soft magnet. In exchange spring media, the soft magnet is usually placed above the hard layer.

If our model is used as conventional perpendicular media and if we would simply assume uniform rotation of the magnetization, the energy barrier of a grain would be written as $E_B = K_U V_{\text{grain}} = 5.8 \times 10^{-19} \text{ J}$. However, the energy barrier of the patterned media can be described as $E_B = 4F \sqrt{AK_U} = 7.6 \times 10^{-18} \text{ J}$. In the last formula, it was assumed that the lateral dimensions of the patterned element are larger than the domain-wall width. In this case, reversal occurs via domain wall motion. $F$ is the product of the film thickness times the smaller edge length of the patterned element. This enables us to use small $K_U$ materials. Hence, one can write with conventional perpendicular heads.

![Fig. 2](image1.png)

**Fig. 2.** Transient states during reversal of one hard magnetic island are shown. The z-component of the magnetization is represented by the gray scale map. (a) For $A_{\text{int}} = 0.075 \text{ pJ/m}$, the upper right bit cannot be recorded, (b) successful writing with $A_{\text{int}} = 0.37 \text{ pJ/m}$.

![Fig. 3](image2.png)

**Fig. 3.** Transient states during reversal of one hard magnetic island are shown. Recording process of 3, 4 and 7 ns are shown for $A_{\text{int}} = 0.75 \text{ pJ/m}$ (a), and $A_{\text{int}} = 1.13 \text{ pJ/m}$ (b).
Too strong intergrain exchange coupling may lead to the erasure of the adjacent tracks. In the case of $A_{\text{int}} = 1.13 \text{ pJ/m}$ (high intergrain exchange; shown in Fig. 3b) the switching of the selected bit may induce reversal of neighboring bits. Bits in the down track directions as well as in cross track direction may be reversed. Fig. 3a shows one other type of adjacent track erasure which was observed in the intermediate intergrain exchange regime ($A_{\text{int}} = 0.75 \text{ pJ/m}$). During the first 3 ns the head field points in the $+z$ direction. At 4 ns, when the head field already points in $-z$ direction, the magnetization of the upper right bit and its surroundings are reversed. It is very interesting to note that 3 ns later, at 7 ns, one can see that the lower left bit has reversed its magnetization. This reversal is initiated by the head field which changed its direction from $-z$ to $+z$. The fluctuations can be seen in a movie which can be downloaded from Ref. [23].

When the head field on the upper right bit is switched, the magnetization of the media is reversed. The soft magnet reverses earlier and the hard magnet a bit later. The reversal process excites magnetic fluctuations in the soft magnetic region. Due to the fluctuation induced by the head reversal, the lower left bit reverses.

In conclusion, fully integrated micromagnetics simulations were performed to simulate a polycrystalline magnetic recording layer with varying intergrain exchange. The right choice of the intergrain exchange is crucial for patterned media. A too low value leads to undesired high switching fields and leads to a reduction of the thermal stability. A too large value will induce adjacent track erasure and will reduce the signal-to-noise ratio. Our preliminary studies suggest an optimal value around 0.37 pJ/m. The adjacent bit/track erasure of $A_{\text{int}} = 1.13 \text{ J/m}$ is shown in Fig. 1.

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